Visual Pre-attentive Processing and Pattern Formation

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Perceiving the visual world is foundational to human experience, with pre-attentive processing playing a pivotal role in rapidly detecting and interpreting visual patterns. Through millennia of evolution, humans have refined their ability to discern visual cues, crucial for survival and adaptation to environmental challenges. Recent studies indicate that humans can discern visual patterns within approximately 250 milliseconds, shaping their initial impressions of the visual environment. This understanding of the neurological processes involved in visual pattern detection empowers interaction designers to craft coherent and accessible designs, incorporating well-structured visual hierarchies that facilitate critical decision-making in split-second scenarios. Visual analysis is functionally divided between an early preattentive level of processing at which simple features are coded spatially in parallel and a later stage at which focused attention is required to conjoin the separate features into coherent objects (Treisman, 1994). This paper will focus on the former, followed by a scientific design review of an Air Quality Index website dashboard.

Process of Visual Search

Visual search is the act of looking for a predefined target among other objects. The need to search is a manifestation of attention: since we cannot process everything, we have to select, and to select the right object we need to search (Chan & Hayward, 2013). The search is facilitated through rapid eye movements called *saccades*, which shift our line of sight between successive points of fixation and point the fovea at objects of interest (Becker 1989; Leigh and Zee, 1999). It is important to note, however, that even the biggest saccades last only ~100 ms, which is less than the response time of the visual system. Thus, saccades are ballistic movements. There is no time for visual feedback and accuracy depends on internal monitoring of neural signals (Leigh & Kennard, 2003).

Many visual search theories have been posited over the past 50 years. The Feature Integration Theory (FIT), proposed by Treisman (1994) suggested the concept of an initial, “preattentive” stage of processing, in which a limited set of basic features like color and orientation could be processed in parallel across the visual field. Specifically, she proposed that feature search was parallel because, preattentive processing is sufficient for detecting a feature, whereas conjunctive search (a visual search process that involves identifying a target surrounded by distractors that share some of the target's features) is serial because focal attention is needed for identifying feature conjunctions.

In 1989, Wolfe, Cave, and Franzel (1989) proposed that the preattentive feature information could be used to “guide” the serial deployment of attention; hence the name of the model, “Guided Search” (GS). Attention will be deployed to the most active location on the map. Attentional priority is determined by a combination of bottom-up salience and top-down guidance in a weighted manner to direct attention to the next item or location. The core difference between the two theories was that, while FIT proposed a dichotomy between parallel and serial search tasks, GS proposed a continuum based on the effectiveness of guidance. (Wolfe, 2021)

Neurological Journey in Pre-Attentive Processing

Visual information travels from the retina to the brain primarily via the geniculo-striate pathway, which connects the retina to the primary visual cortex (V1). This pathway is crucial for high-level visual processing and pattern recognition, operating through rapid feed-forward processing. Through hierarchical and automatic processes, it facilitates the initial representation and analysis of visual scenes (De Moraes, 2013; Lamme, 1998).

Journey within the Retina

The retina, a complex neural structure, features vertical connections leading to the brain from photoreceptors to bipolar cells to retinal ganglion cells. Horizontal connections between these pathways exist through interneurons called horizontal cells and amacrine cells. Photoreceptors, including rods and cones, initiate visual perception by detecting photons and converting light into neurotransmitter release through phototransduction (Swanston and Wade, 2001).

Horizontal Cells

Horizontal cells are multi-purpose outer neurons located in the outer plexiform layer of the retina. They facilitate lateral communication among photoreceptors and modulate their output. Through a process called lateral inhibition, they isolate the origin of a light signal by minimizing the noise around it by suppressing adjacent photoreceptors. This contributes to the early stage visual processing by enhancing contrast through edge detection and color opponency (Chapot et al., 2017).

Bipolar Cells

Bipolar cells serve as the primary neurons linking the photoreceptor output to the retinal ganglion cells that, in turn, provide the retina output to the brain. (Burkhardt, 2010). Functionally, bipolar cells split information into two parallel channels of opposite response polarity via two broad classes of cells: *OFF-cells* hyperpolarize to light and are sensitive to light decrements or dark regions in the visual scene. Whereas, *ON-cells* depolarize and thereby invert the polarity of the photoreceptor input, and are sensitive to light increments or light regions in the visual scene. They are responsible for coding luminance contrast information. (Werblin & Dowling, 1968; Burkhardt, 2010). They also send axonal projections to the amacrine cells.

Amacrine Cells

Amacrine cells, found in the inner plexiform layer of the retina, regulate signal transmission between bipolar cells, horizontal cells, and retinal ganglion cells. They aid edge detection by inhibiting neighboring cells, refining spatial information, and enhancing contrast along edges. This process shapes the receptive fields and response properties of retinal ganglion cells, crucial for perceiving edges and boundaries in the visual scene (Masland, 2013). Together, horizontal, bipolar, and amacrine cells lay the foundation for the *figure-ground principle*, by helping differentiate between an object and its surroundings based on grouping within an identified *boundary of region*.

Retinal Ganglion Cells

Retinal ganglion cells (RGCs) are the primary conveyors of visual information from the retina to the brain. They play a critical role in shaping our perception of the world. Unlike the pixel representation of a visual scene captured by the photoreceptors, RGCs transmit highly processed visual information in the form of action potentials (or nerve impulses), extracted in parallel from different attributes of a visual scene — spatial contrast, color, motion, flicker, fine and coarse textures, absolute light level — and deliver this information to different sites within the visual system. At least 18 different types of ganglion cells are now thought to be present in the primate and human retina, all of them functionally and morphologically distinct. The individual types gain their functional specificities in turn from dedicated circuits that lie between the photoreceptors and the ganglion cells (Kim et al., 2021).

The receptive field of a retinal ganglion cell determines the region of the retina where visual stimuli affect its firing rate, indicating the area to which the neuron responds. RGCs are classified as ON, OFF, or ON-OFF based on whether their firing rate increases at the onset, offset, or both phases of a light stimulus. Receptive fields follow a center-surround organization, where light on the center may increase firing (excitation) while light on the surround may decrease firing (inhibition), crucial for edge detection and contrast enhancement in visual processing (Sanes and Masland, 2015).

Optic Nerve and Optic Chiasma

The axons of the retinal ganglion cells leave the eye forming the *optic nerve*. This nerve is situated at the base of the brain, and the two optic nerves travel toward one another and appear to meet at the *optic chiasm*, but don't; instead, they project to different cerebral hemispheres according to the area of the retina from which they originate: Axons from the outer (temporal) side of each retina (the left half-retina for the left eye and the right half-retina for the right eye) project to the *ipsilateral hemisphere* (on the same side), and the axons from the nasal halves of the retinas cross over and project to the *contralateral hemisphere*. There is a narrow vertical strip in the center of both retinas, subtending about 1°, that projects to both hemispheres. (Swanston & Wade, 2013)

Lateral Geniculate Nucleus

Following the optic chiasm, axons from retinal ganglion cells extend into the optic tract, forming synaptic connections in the thalamus at a 6-layered structure known as the lateral geniculate nucleus (LGN). Ganglion cell axons from the *ipsilateral ey*e (temporal retina) synapse in layers 2, 3, and 5, while axons from the *contralateral eye* (nasal retina) synapse in layers 1, 4, and 6. (De Moraes, 2013)

Two main types of neurons can be identified in the LGN. Layers 1 and 2, called *magnocellular layers*, have large neurons (called *M-cells*), which are involved in the perception of motion, depth, and other dynamic aspects of visual stimuli. Layers 3, 4, 5, and 6, called *parvocellular layers*, have small neurons (called *P-cells*), which are sensitive to color, fine spatial detail, and slow-moving stimuli, and hence perceive color, form, and texture. There is a third cell layer distributed irregularly between the parvocellular and magnocellular layers called the *koniocellular layer* (with *K-cells*), which is involved in the perception of color information, particularly blue-yellow color signals (Lennie, 1980). Overall, each layer represents a distinct pathway for processing different aspects of visual information, including motion, form, spatial detail, color, and color opponency, contributing to the rich and multifaceted experience of visual perception.

Visual Cortex

Although the cortex is in many ways a uniform structure, different regions of the cortex are devoted to very different purposes, ranging from sensory perception to motor control to higher intellectual functions. Within the sensory cortex, one finds a further spatial segregation of the modalities.

Primary Visual Cortex (V1)

Axons from the six layers of the LGN travel along the optic radiations and synapse in the primary visual cortex, named V1. These axons make connections in the cortical layer IV ('stripe of Gennari'). The visual cortex corresponds to approximately 55% of the entire cortical area of the primate brain and is responsible for 40% of the visual processing (De Moraes, 2013; Lennie, 1980). V1 is a highly organized structure. It breaks down the pattern of light falling on the eye into discrete features, such as retinal location, orientation, movement, and wavelength, as well as maintaining a difference between the signals from the two eyes.

The cells in layer IV that receive their inputs from the M pathway, called *orientation-selective neurons*, are excited by lines or edges in a specific orientation, particularly if they are moving. For example, a given cell might respond most strongly when a horizontal line moves vertically. After their discovery, by David Hubel and Torsten Wiesel in 1959, they became called *feature detectors*; their projections are known as *feature maps*. This was because the cortical neurons were selectively tuned to extract certain features contained in the pattern of retinal stimulation. Other features extracted include the direction of edge motion, binocular disparity (the slight difference in the retinal images of an object that is seen by each eye), and color (Swanston & Wade, 2001).

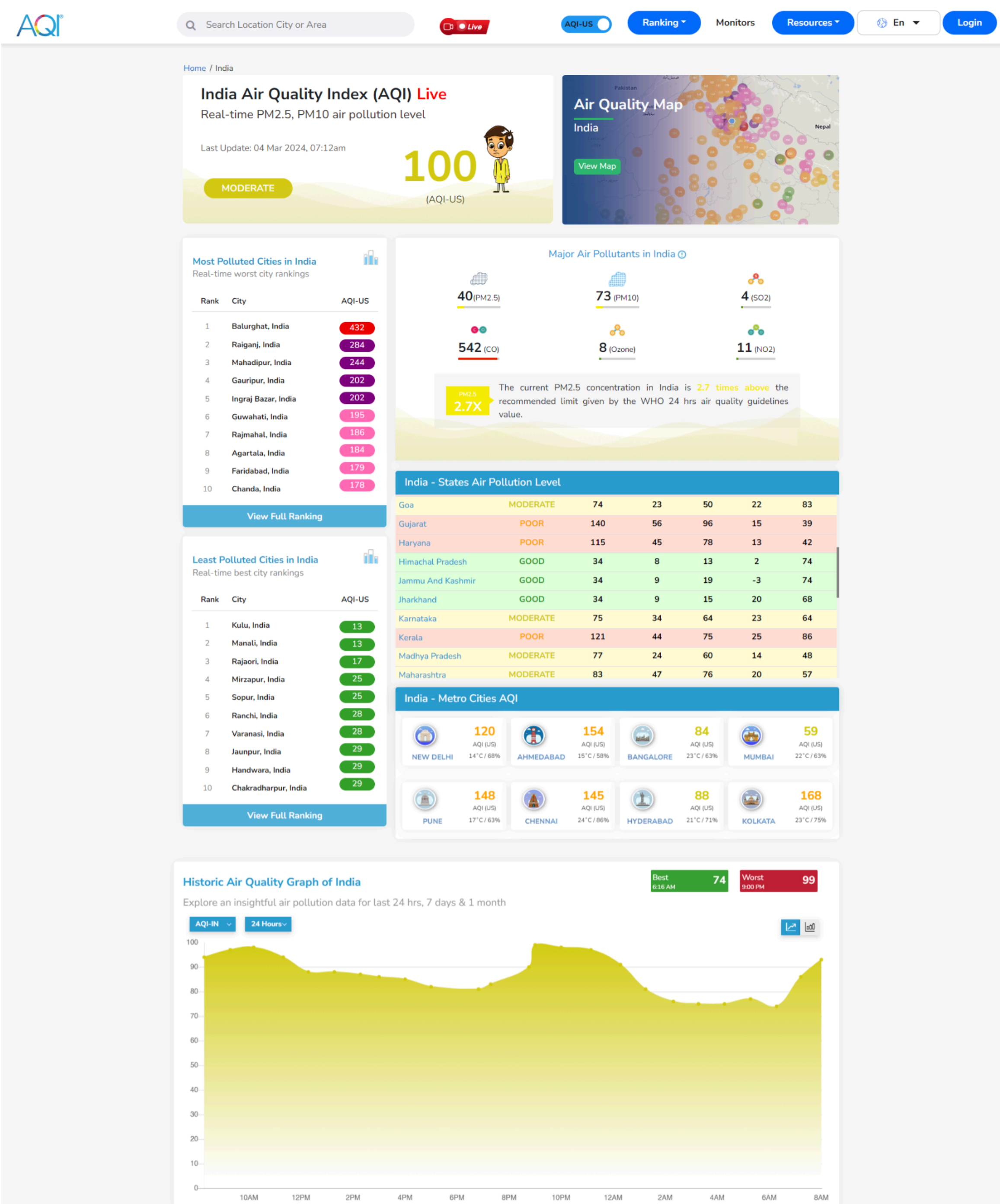
These features are further differentiated in the subsequent cortical processing in visual areas. Axons from neurons in V1 project to a variety of other visual areas in the cortex. (Swanston & Wade, 2001)

Secondary Visual Cortex (V2)

The adjacent visual area (V2) receives inputs from the three receptive field types in V1. In V2 there are binocular cells that respond most strongly when the receptive field characteristics are slightly different. These have been called *disparity detectors* because they appear to be responding to specific disparities between the stimulating edges in each eye. When there is lack of disparity, or in other words, similarity, between objects, the human brain tends to group them as one; this is consistent with the psychophysical *principle of similarity*.

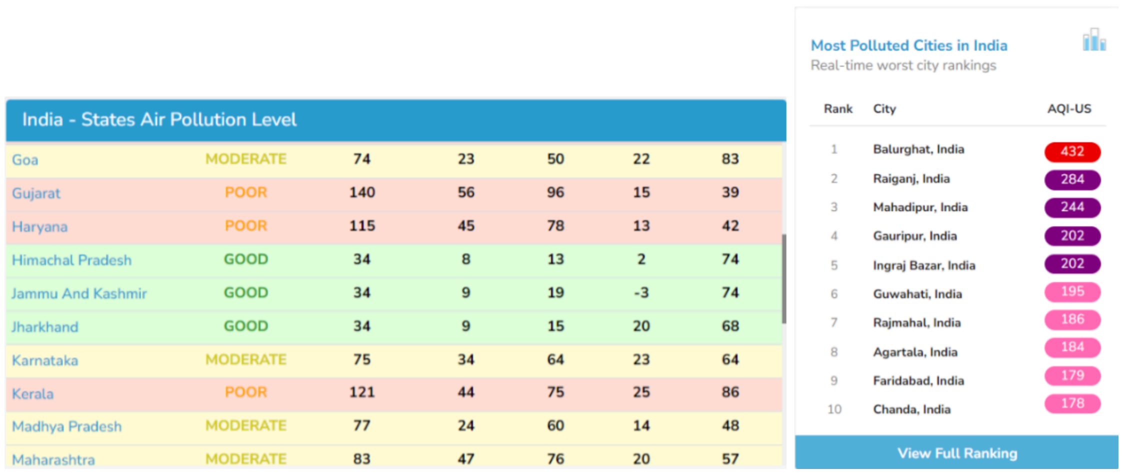
The projections from the retina to the LGN and onwards to the multiple visual areas retain the basic mapping of the retinal surface: Adjacent regions on the retina project to adjacent regions in LGN, V1, V2, etc. This is called a *retinotopic map* or *master map* because the distribution of stimulation on the retina is preserved at more central sites. In turn, the pattern of retinal stimulation is geometrically related to the layout of objects in space. This is consistent with the psychophysical *principle of proximity* where objects that are close to each other in space are more likely to be perceived as belonging together (Wagemans et al., 2012).

Design Review of Air Quality Index (AQI) Dashboard



Positives

1. **Closed Regions.** Every section of the dashboard has been grouped separately into rectangular boxes. The shadow around each box makes it easy to detect the edges, and perceive each box as a separate section.
2. **Similarity**. (See image below) In the table depicting levels of air pollution in each state, the background color of each row is intended to represent the degree of AQI. In the list of most polluted cities in India as well, the AQI levels have been color-coded. Even without understanding what each color means, it is evident that those states that have the same colors have similar levels of pollution.



India - States Air Pollution Level

Goa	MODERATE	74	23	50	22	83
Gujarat	POOR	140	56	96	15	39
Haryana	POOR	115	45	78	13	42
Himachal Pradesh	GOOD	34	8	13	2	74
Jammu And Kashmir	GOOD	34	9	19	-3	74
Jharkhand	GOOD	34	9	15	20	68
Karnataka	MODERATE	75	34	64	23	64
Kerala	POOR	121	44	75	25	86
Madhya Pradesh	MODERATE	77	24	60	14	48
Maharashtra	MODERATE	83	47	76	20	57

Most Polluted Cities in India
Real-time worst city rankings

Rank	City	AQI-US
1	Balurghat, India	432
2	Raiganj, India	284
3	Mahadipur, India	244
4	Gauripur, India	202
5	Ingraj Bazar, India	202
6	Guwahati, India	195
7	Rajmahal, India	186
8	Agartala, India	184
9	Faridabad, India	179
10	Chanda, India	178

View Full Ranking

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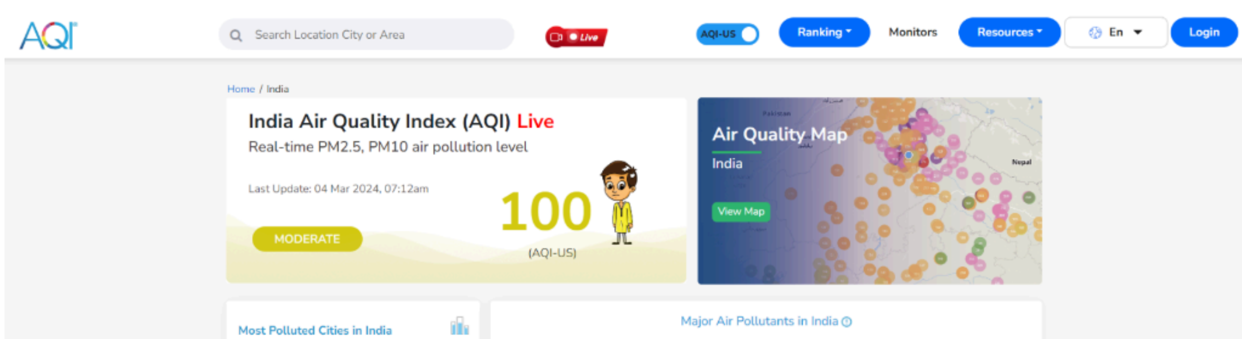
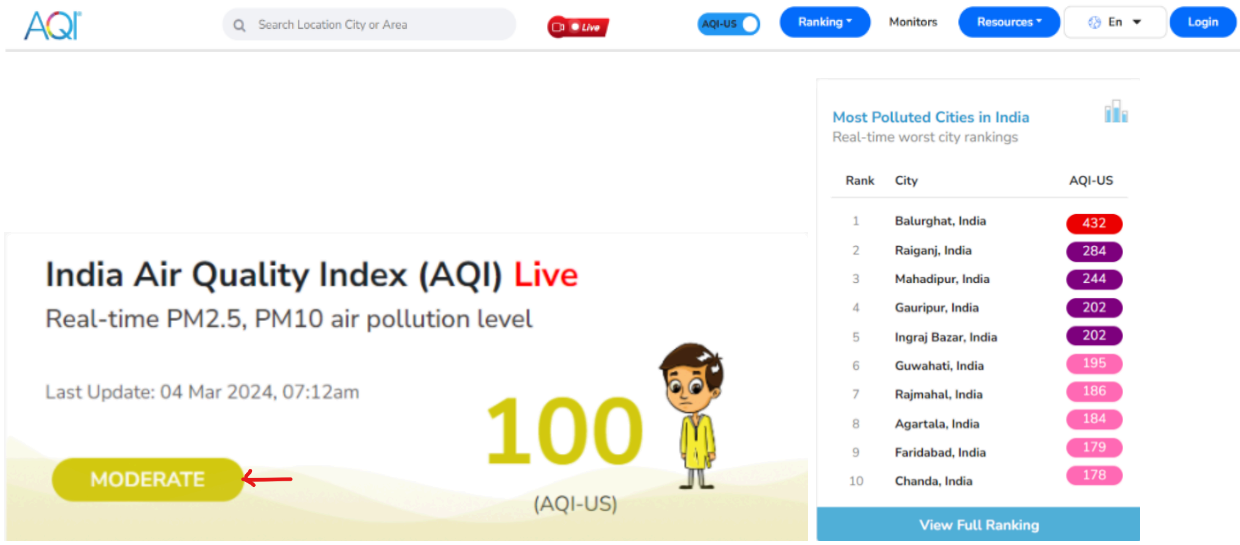
3. **Proximity**. (See image below) There is significant white space between the menu bar and the rest of the page to indicate the separation in the content type. There is relatively much lesser white space between the individual sections indicating the AQI to show that these sections are covering closely related content.



Negatives

1. **Similarity**. (See image below) The buttons in the menu bar are shaped as rounded rectangles and are clickable. The indicators of rating of AQI in the top section and the AQI numbers in the list of cities are also shaped as rounded rectangles. However, they are not buttons, and are not clickable. Choosing a different shape for the AQI indicators would avoid confusion among users.



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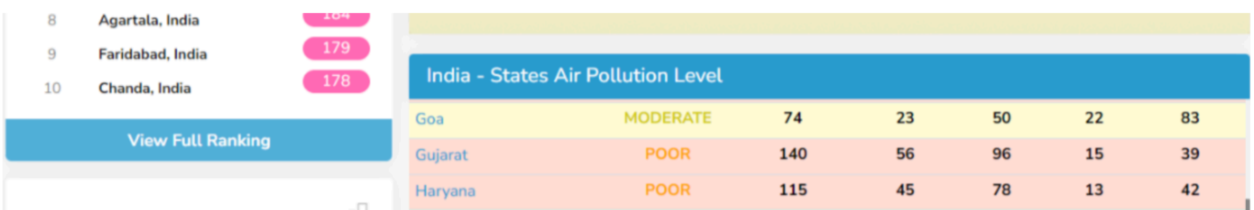
Another case of unintentional similarity is visible in the image below. “View Full Ranking” is a button, and “India - States Air Pollution Level” is a section heading. Styling them similarly, and also placing them right next to each other is confusing for the user. It would instead be smarter to use one template for headings of all sections and a different one for all buttons on the page. Changing the shape of the “View Full Ranking” to a rounded rectangle, similar to the buttons on the menu bar would be better to depict consistency across the page.



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2. **Proximity**. The spacing between options on the menu bar is not consistent. As of now, the Login button, language selection dropdown and the Resources dropdown are placed closer to each other, indicating some relationship when there is none. Better spacing would show more clarity.

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Conclusion

Perceiving the visual world is fundamental to human experience, with pre-attentive processing enabling rapid detection and analysis of visual patterns critical for survival and adaptation. Understanding the neurological journey of visual pattern detection aids interaction designers in crafting intuitive designs, leveraging principles like proximity and similarity to create coherent visual hierarchies for efficient decision-making and user engagement.

References

Becker, W., & Jürgens, R. (1990). Human oblique saccades: quantitative analysis of the relation between horizontal and vertical components. *Vision research*, *30*(6), 893-920.

Burkhardt, D. A. (2011). Contrast processing by ON and OFF bipolar cells. *Visual neuroscience*, *28*(1), 69-75.

Chan, L. K. H., & Hayward, W. G. (2013). Visual search. *Wiley Interdisciplinary Reviews: Cognitive Science*, *4*(4), 415–429. https://doi.org/10.1002/wcs.1235

Chapot, C. A., Euler, T., & Schubert, T. (2017). How do horizontal cells 'talk' to cone photoreceptors? Different levels of complexity at the cone-horizontal cell synapse. *The Journal of physiology*, *595*(16), 5495–5506. https://doi.org/10.1113/JP274177

De Moraes, C. G. (2013). Anatomy of the visual pathways. *Journal of glaucoma*, *22*, S2-S7.

Kim, U. S., Mahroo, O. A., Mollon, J. D., & Yu-Wai-Man, P. (2021). Retinal ganglion cells—diversity of cell types and clinical relevance. *Frontiers in neurology*, *12*, 661938.

Lamme, V. A., Super, H., & Spekreijse, H. (1998). Feedforward, horizontal, and feedback processing in the visual cortex. *Current opinion in neurobiology*, *8*(4), 529-535.

Leigh, R. J., & Kennard, C. (2004). Using saccades as a research tool in the clinical neurosciences. *Brain*, *127*(3), 460-477.

Leigh, R. J., & Zee, D. S. (2015). *The neurology of eye movements*. Contemporary Neurology.

Lennie, P. (1980). Parallel visual pathways: a review. *Vision research*, *20*(7), 561-594.

Lim, A. (2021). Sensation and Perception: The Visual System. In D. Simmons & A. Morales (Eds.), *Open Neuroscience Initiative*. https://www.austinlim.com/open-neuroscience-initiative?msclkid=eace2a59c69411ecbf6348d5d4d5d27e

Masland R. H. (2012). The tasks of amacrine cells. *Visual neuroscience*, *29*(1), 3–9. https://doi.org/10.1017/s0952523811000344

Treisman, A. M., & Kanwisher, N. G. (1998). Perceiving visually presented objets: recognition, awareness, and modularity. Current opinion in neurobiology, 8(2), 218-226.

Wade, N., & Swanston, M. (2013). *Visual perception: An introduction*. Psychology Press.

Wagemans, J., Feldman, J., Gepshtein, S., Kimchi, R., Pomerantz, J. R., van der Helm, P. A., & van Leeuwen, C. (2012). A century of Gestalt psychology in visual perception: II. Conceptual and theoretical foundations. *Psychological Bulletin*, *138*(6), 1218–1252. https://doi.org/10.1037/a0029334

Werblin, F.S. & Dowling, J.E. (1968). Organization of the retina of the mudpuppy, Necturus maculosus. II. Intracellular recording. Journal of Neurophysiology 32, 339–355.

Wolfe, J. M. (1994). Guided search 2.0 a revised model of visual search. *Psychonomic bulletin & review*, *1*, 202-238.

Wolfe, J. M. (2021). Guided Search 6.0: An updated model of visual search. *Psychonomic Bulletin & Review*, *28*(4), 1060-1092.